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Remote Condition Sensing and Analysis of Army Facilities: System Design, Creation, and Implementation

by
Donald K. Hicks
Glenn Rasmussen

The repair of moisture-related damage to Army facilities is a major expense in terms of both labor time requirements and money spent. Most such repairs are unscheduled and demand immediate attention, which disrupts normal work schedules and interferes with other elements of the Army's facility-maintenance program. The discovery and repair of water damage in its early stages would save money and promote greater maintenance efficiency.

This research addresses the design, creation, and implementation of a prototype condition sensing and analysis system capable of remotely detecting and reporting water damage in its early stages. This system would use electronic sensors and microcomputer technology to accurately capture and transfer water damage data without requiring visual inspection by personnel at the building site.

This interim report describes the testing methodology, site selection, procedures for data collection and transfer, and the approach to data evaluation for a prototype system installed in a test structure at Fort Benjamin Harrison, IN.

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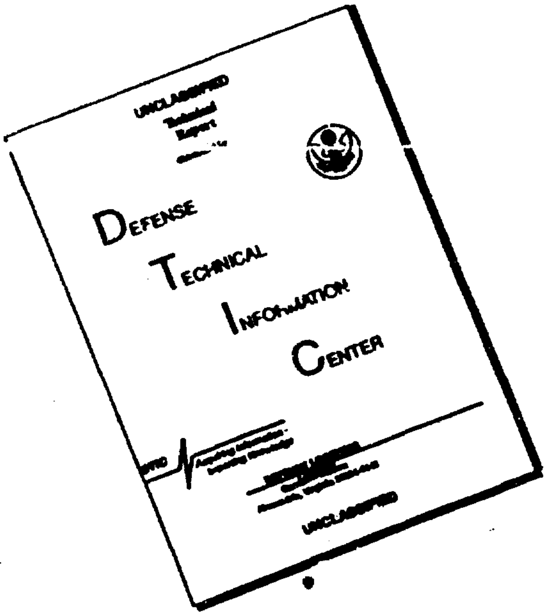

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FOREWORD

This research was conducted for the U.S. Army Engineering and Housing Support Center, Directorate of Facilities Engineering, under Operations and Maintenance, Army Order FAD 88-080037; Work Unit RU8, "Building Condition Monitoring." The USAEHSC technical monitor is Mr. Michael Smith, CEHSC-FB.

The work was performed by the Facilities Systems (FS) Division, U.S. Army Construction Engineering Research Laboratory (USACERL). Donald K. Hicks was Principal Investigator and Glenn A. Rasmussen was Associate Investigator. Dr. Michael O'Connor is the Chief of FS. The USACERL technical editor was Gordon L. Cohen, Information Management Office.

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REMOTE CONDITION SENSING AND ANALYSIS OF ARMY FACILITIES: SYSTEM DESIGN, CREATION, AND IMPLEMENTATION

1 INTRODUCTION

Background

U.S. Army installation Directorate of Engineering and Housing (DEH) building managers have long known that the repair of moisture-related damage is a major expenditure in work hours and dollars because most of these repairs are of an unscheduled nature demanding immediate attention. These repairs disrupt normal work schedules and decrease DEH maintenance efficiency in other areas.

According to the American Society of Testing Materials (ASTM), "except for structural errors, about 90 percent of all building construction problems are associated with water in some way."[1] Researchers at the University of Illinois Small Homes Council/Building Research Council surveyed over 600 residences in Champaign County, Illinois, and found that 5.4 percent of the structures had major moisture damage and another 35 percent suffered damage ranging from minor to moderate.[2] This damage was in the form of:

1. Decrease of thermal resistance through wet insulation
2. Corrosion of metal
3. Decay of wood and wood products
4. Undesirable expansion of building materials
5. Growth of fungus or mold
6. Leaching of salts from brick or masonry
7. Short circuits in electrical wiring
8. Paint failure
9. Discoloration of building material
10. Infestation by woodboring insects when the fiber saturation point (30 percent of the wood's dry weight) is reached.

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[1] M. Lieff and H. R. Trechsel, eds., *Moisture Migration in Buildings* (ASTM 779, Baltimore, MD, 1982), p 1.

[2] W. B. Rose, "Moisture Damage to Homes in Champaign County, Illinois," *Condensation and Related Moisture Problems in the Home* (American Association of Housing Educators and Small Council - Building Research Council, University of Illinois, Urbana-Champaign, IL, 1988), p 74.

Numerous work hours are lost each year because of indoor environmental factors that adversely affect the work and living environment. Moisture damage can promote indoor pollutants (e.g., mold, mildew) that can threaten the health of a building's occupants. It can also corrode containers or equipment containing hazardous materials (e.g., refrigeration lines), increasing the danger of indoor release of such materials. The Army is increasingly concerned with indoor environmental hazards that reduce personnel performance and jeopardize employee welfare.

The U.S. Army Construction Engineering Research Laboratory (USACERL) has been tasked with the research and development of a state-of-the-art condition sensing system that would enable a DEH manager to efficiently recognize building damage and hazards to health and safety. Remote sensing technology has in recent years been used in an increasingly wide variety of innovative applications (e.g., infrared, side-looking radar, high-resolution satellite photography).[3] This technology is a logical choice for investigation in this effort to support the Army's continuing goals of improving efficiency and preserving assets.

The development of a condition analysis system—an expert system capable of diagnosing building problems based on sensor input, and reporting those problems to the proper authority when repair is most cost-efficient and least disruptive to normal routine—is intended to be a major end product of this research. This study is a first step toward that end. Should a condition analysis system ultimately be determined feasible, integration with other building intelligence systems currently in use (e.g., Energy Control Monitoring System [ECMS]) would be a further goal. The combined systems could then be built into new buildings during construction at a relatively small increase in the total cost of construction.

Objectives

The objective of this phase of research is to design, create, and implement a prototype remote condition sensing and analysis system. Issues to be addressed include testing methodology, site selection, equipment selection, and data collection, transfer, and evaluation. Objectives of the overall research are to:

1. Determine the factors involved in causing moisture-related building damage, and identify additional factors that may adversely affect the ability of building occupants to perform their missions

2. Quantify the feasibility of using leading-edge technology for remotely monitoring building areas not subject to routine scheduled visual inspections (e.g., attics, crawlspaces, interstitial spaces) for moisture, moisture-related damage, and conditions threatening health and safety

3. Process the data into a model that will accurately predict the need for corrective action.

Approach

Data are being collected from sensors installed in a building known to be suffering from moisture-related damage. The building is located in a temperate climatic zone with temperatures ranging from

[3] R. Tucker, "Improving Productivity," *The Military Engineer*, Vol 80, No. 524 (September/October 1988), p 512.

below 0 °F in winter to above 100 °F* in summer and moderate annual levels of moisture from rain and snow. Appropriate sensors with the ability to monitor for hazardous environmental conditions are being investigated and evaluated for inclusion in this study.

Scope

The overall study focuses on analyzing factors affecting moisture levels and moisture damage in one Army building. The determination of potential health and safety factors influencing personnel performance will also be addressed. Secondary investigation will examine current sensing technology and data transfer techniques. This phase of the study does not address moisture control, methods for the repair of moisture damage, or health and safety standards.

Mode of Technology Transfer

The findings of this study will impact the Corps of Engineers Guide Specifications, Military Construction and Repair and Preventive Maintenance Activities as cited in AR 420-22 and related technical manuals (TM 5-600 series). Technology transfer will occur through technical reports and system demonstrations at selected Army installations.

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*U.S. Standard units of measure are used throughout this report. A metric conversion table can be found on p 25.

2 TESTING METHODOLOGY

Overview

Sensor technology has been advancing and sensors have become available at a reasonable cost. The combination of leading-edge sensor technology and state-of-the-art microprocessor technology creates the possibility of a cost-effective, "intelligent" building.

Environmental deterioration and resource conservation have created a national awareness which has led to building designs where energy conservation is of highest priority. As a result, newly constructed buildings are significantly more resistant to air infiltration. New and different moisture problems are appearing, and they need to be investigated and resolved. As building envelope technology advances, the occurrence of moisture problems and related damage increases proportionally. The dynamics of moisture generation and transfer, and the problems they cause in buildings are just beginning to be identified and understood.

Testing

One task of this study is to sense the amount of moisture present in the form of vapor, condensation, liquid, or ice that is damaging building components. A condition or situation that is capable of causing a response in a sensor and can be observed and captured for analysis is defined as "sensorable" for the purpose of this test. By using remote sensors, data will be collected from a single building, as Figure 1 illustrates This data, collected over the period of the test, will provide information necessary to evaluate the actual state of sensor technology and its application to condition diagnosis in current and future Army buildings.

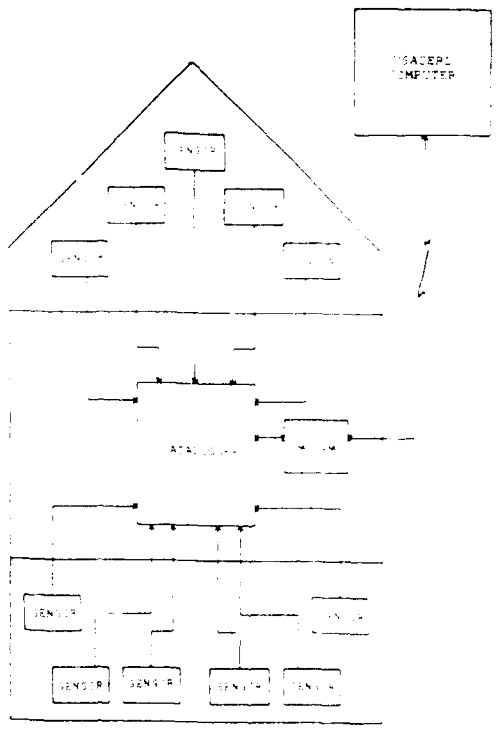


Figure 1. Diagram of system concept.

3 SITE SELECTION

Site Criteria

The site selection process addressed the factors of building composition, climatic conditions throughout the year, and evidence of moisture damage.

Building Type

A test building ideal to illustrate worst possible conditions and greatest susceptibility to damage would be of wood frame construction with a clay brick veneer. The substructure would be of either poured-in-place concrete or masonry. A basement area, crawlspace, or combination of the two would be present within the structure. Also, a pitched roof with an intact envelope system that creates an attic space is considered necessary for the test. A mechanical area that supplies heating, cooling, and hot and cold water, as well as waste evacuation systems, should be located within the exterior walls. Interstitial spaces should be present in some form. Insulation should maintain normal occupational temperatures in work or living areas without excess energy expenditures. It is assumed that personnel would occupy the building almost daily, depending on its usage.

Climatic Conditions

The building chosen should be located in the North Temperate Zone (between the Tropic of Cancer and the Arctic Circle) where the climatic conditions would best illustrate the maximum and minimum weather potential. More specifically, the site should be within the mid-latitude humid region of the zone, which experiences a full range of seasonal weather conditions, including hot summers, cold winters, and substantial precipitation throughout the year (Figure 2).

Evidence of Moisture Damage

The building chosen to develop a model for damage prediction should have visible signs of moisture-related damage. The presence of damage is more significant than the type of damage. If the building chosen does not develop moisture damage after a long time, the collection of relevant data will be unnecessarily delayed. Monitoring existing damage allows tracking and evaluating long-term trends. Tracking indoor and outdoor temperature and humidity is also desirable; such data will enhance the determination of cause-and-effect relationships.

General Location

Initially, four U.S. Army installations located within the preferred climatic region were considered for testing (Figure 3):

1. Fort Riley, KS

2. Rock Island Arsenal, IL

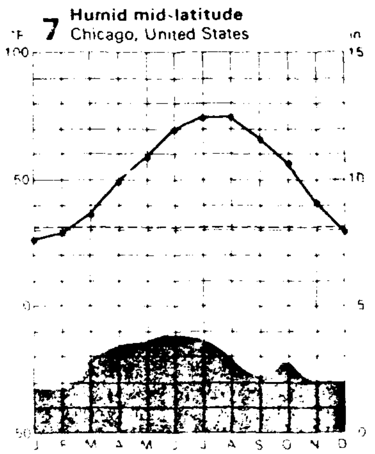
3. Fort Knox, KY

4. Fort Benjamin Harrison, IN.

Fort Riley was not selected because it is too close to the western edge of the mid-latitude humid region, which would require an extended period of data collection if weather conditions atypical of the humid zone (such as the 1988-89 drought) were to develop. Rock Island Arsenal was not selected because it is too close to the Mississippi River, where the higher humidity levels generated by the river could not be considered average for the targeted region. Fort Knox was eliminated because the cold winter conditions desirable for the test site were too short to establish a trackable cycle. Fort Benjamin Harrison was determined the best site because of its central location (39.43 degrees north latitude, 86.09 degrees west longitude) in the North Temperate Zone and the mid-latitude humid region. The compiled weather data, shown in Table 1, confirmed this choice.

a. The mid-latitude humid region (darkest area).

b. Desired typical yearly temperature ranges for study site.



Representative Climate Conditions

- Mean annual high temperature frequency (above 90°F)—*28 days*
- Mean annual cooling degree-days (above 65°F)—*1100*
- Mean annual heating degree-days (below 65°F)—*5500*
- Mean annual hours of sunshine—*2650*
- Mean annual precipitation—*40 in.*

Figure 2. Basic climatic conditions sought for study site. (Source: *The New International Atlas* [©Rand McNally & Co., Chicago/New York/San Francisco, 1980], pp 314, 315; and *The National Atlas of the United States of America* [U.S. Department of the Interior Geological Survey, 1970], pp 96, 97, 108, 109.)

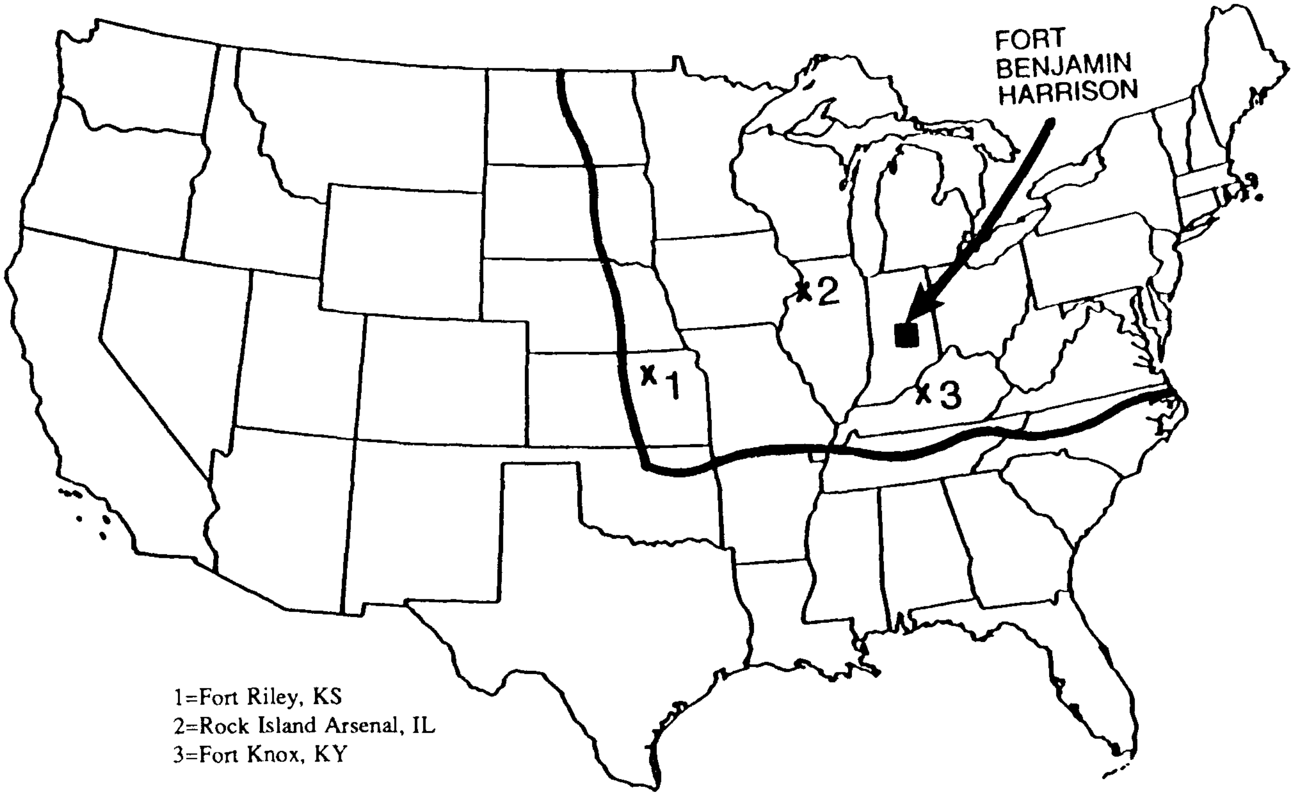


Figure 3. Candidate installations in mid-latitude humid region.

Building Choice

Fort Benjamin Harrison was visited on 1 July 1988 to find a building suitable for the test. Table 2 lists the eight buildings visited on that date. These buildings were among those that the Directorate of Installation Support identified as having some form of moisture problems. The physical structure and moisture condition of each building were examined.

Building 17, the Post Exchange clothing issue point (Figures 4 and 5), was chosen as the test site. Although it is not of wood frame with clay brick veneer, Building 17 fits the ideal-building profile in all other respects. It is a 1-1/2 story structure with exterior walls and substructure of masonry construction and interior framing provided by structural wood components. A masonry fire wall of clay brick bisects the building on all floors. Fire doors are in the basement and on the second floor.

Table 1

Weather Conditions at Fort Benjamin Harrison

MONTH	AVG TEMP °F HIGH†	AVG TEMP °F LOW†	AVG HEATING DEGREE DAYS††	AVG COOLING DEGREE DAYS††	AVG RAINFALL DAYS/MONTH†
JAN	36.0	19.7	1150	0	12
FEB	39.3	22.1	960	0	10
MAR	49.0	30.3	784	0	13
APR	62.8	41.8	387	6	12
MAY	72.9	51.5	159	72	12
JUN	82.3	61.1	11	212	10
JUL	85.4	64.6	0	310	9
AUG	84.0	62.4	5	259	8
SEP	77.7	54.9	63	102	8
OCT	67.0	44.3	302	13	8
NOV	50.5	32.8	699	0	10
DEC	38.7	23.1	1057	0	12

Mean Annual Precipitation 20-40 in.
Mean Annual Snowfall 16-32 in.*

*9 to 10 in. of fallen snow equal 1 in. of rainfall (depending on the moisture content of the snow), based on National Weather Service data.
†Source: James A. Ruffner and Frank E. Blair, eds., *The Weather Almanac* (Gale Research Co., Detroit, 1981) pp 469-470.
††Source: National Weather Service.

Table 2

Candidate Buildings at Fort Benjamin Harrison

Building Number	Building Name/Use	Number of Stories	Exterior Material	Roof Style/ Material	Basement Crawlspace Slab on Grade	Heating System	Approx Age in Years	Comments
422	Motor Pool	1	Brick	Pitched Shingle	Slab on Grade	Steam	40+	Not Appropriate
420/421	Troop Housing	3	Concrete Panel Stucco	Flat Tar/Gravel	Partial Bsmt Slab on Grade	Steam Mech AC	20+	Mechanical Room Problems
410	Mess hall	1	Brick/Glass	Flat Tar/Gravel	Full Crawlspace	Steam Mech AC	10	Excessive Moisture Present
402	Troop	3	Brick Veneer Infill	Pitched Slate	Full Basement	Steam Mech AC	60+	Convection in Mechanical
19	Commissary	1	Brick	Flat Tar/Gravel	Conduit Tunnel Slab on Grade	Steam Mech AC	5+	Not Appropriate
13	Mess hall Food Storage	1 1/2	Brick	Pitched Shingle	Basement & Crawlspace	Steam Mech Cooler	60+	Very Poor Mechanical Room
17	Exchange Clothing Issue	1 1/2	Brick	Pitched Shingle	Full Basement	Steam Mech AC	60+	Roof Sheathing Insulated Fiberglass Bat
622	Post Exchange Offices	2	Brick	Pitched Shingle	Full Basement	Steam Mech AC	60+	Evidence of Recurring Flooding

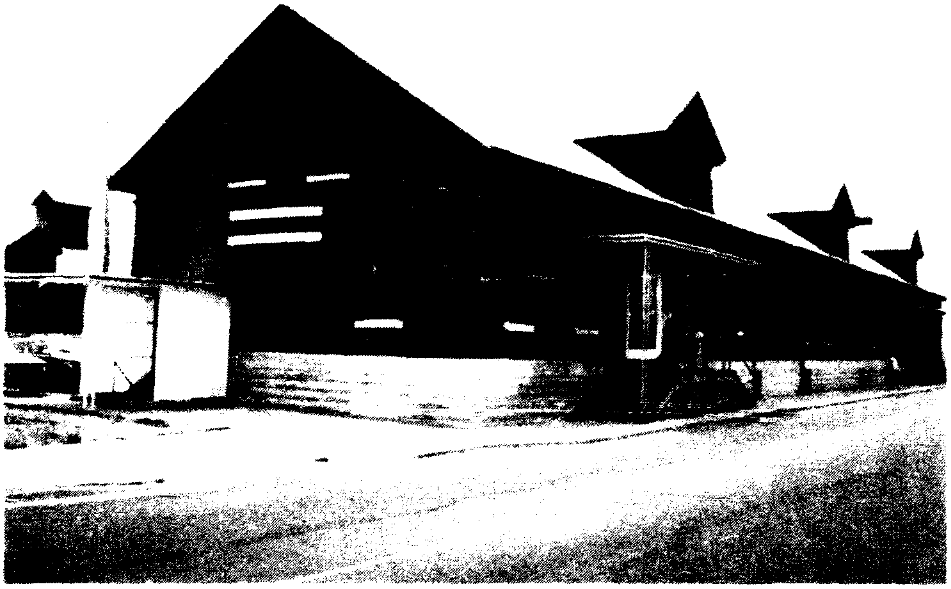


Figure 4. Building 17, east end, front 3/4 view.

Figure 5. Building 17, south rear view.

The building has a full basement (Figure 6) and small adjacent crawlspaces below the loading dock and latrines on the first floor. A mechanical area (Figure 7) is in the west end of the basement. The remaining basement area is used for storage, clothing alterations (Figure 8), and fitting rooms (Figure 9). A door at the east end of the building gives direct access to the basement fitting and alterations area. The first floor (Figure 10) is divided into three areas: retail sales, administration, and clothing alterations. Stairs and sloped merchandise conveyors (Figures 11 and 12) connect the first floor to the basement and second floor (Figure 13).

The second floor is attic space used for merchandise storage and occupied only intermittently (Figure 14). Two hot-water space heaters are suspended from roof trusses about 10 ft from each side of the fire wall on the second floor. Insulation has been applied to the roof sheathing over the length of the building. No vapor barrier is present, however, and the insulation shows evidence of ruptures in the containment envelope in a number of locations.

A variety of moisture-related damage, in the form of mildew, was found above the baseboards on the gypsum board in the basement (Figure 15). Evidence of wetting and drying cycles was found on the floor joists of the first floor (Figures 16 and 17), as was evidence of the start of wet rot in the latrines' interstitial spaces (Figure 18).

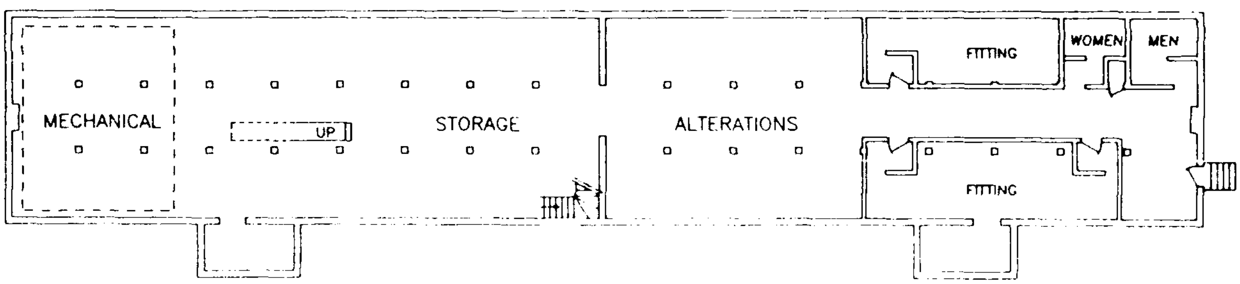


Figure 6. Building 17, basement floor plan.

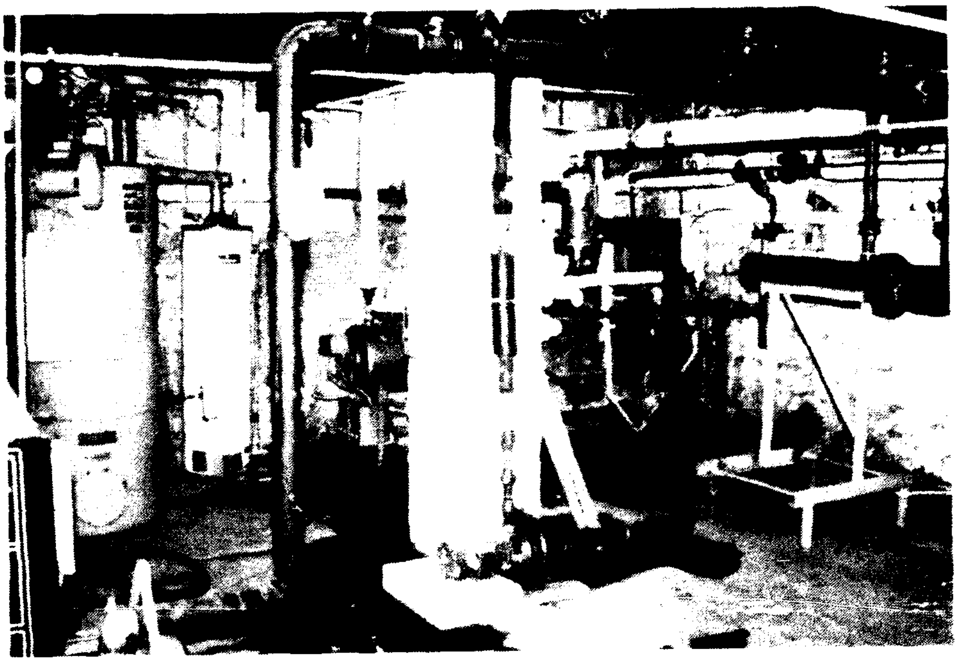


Figure 7. Building 17, mechanical area.

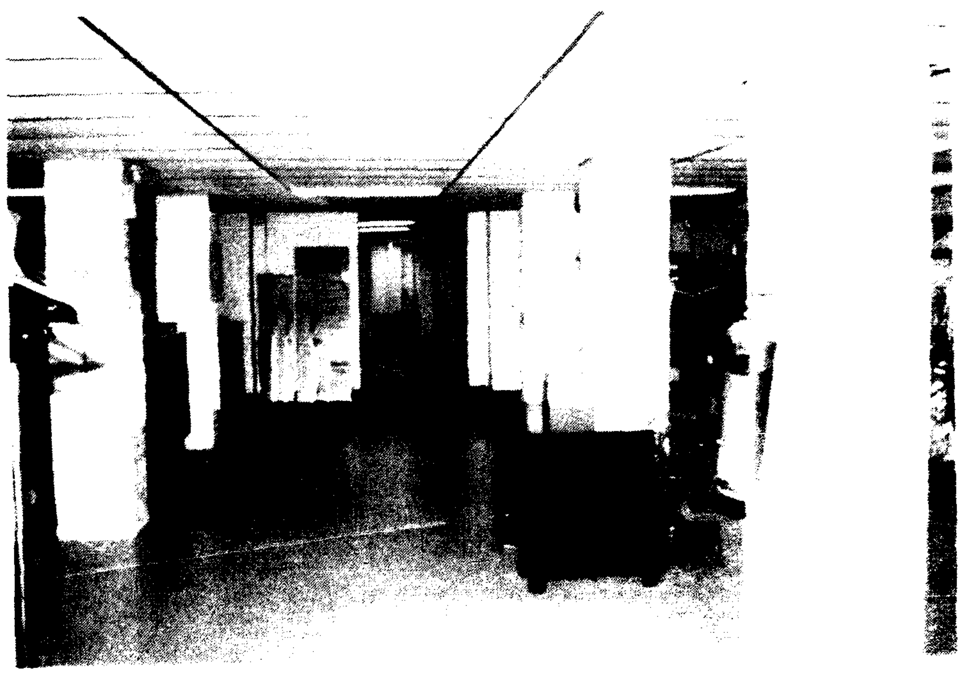


Figure 8. Building 17, basement alterations area.

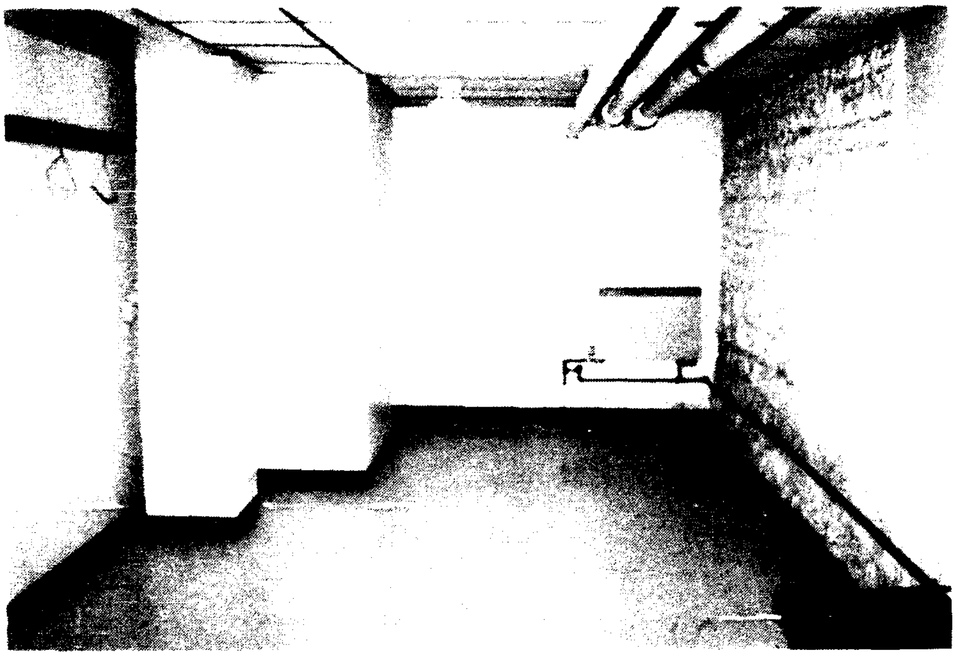


Figure 9. Building 17, basement fitting area, south.

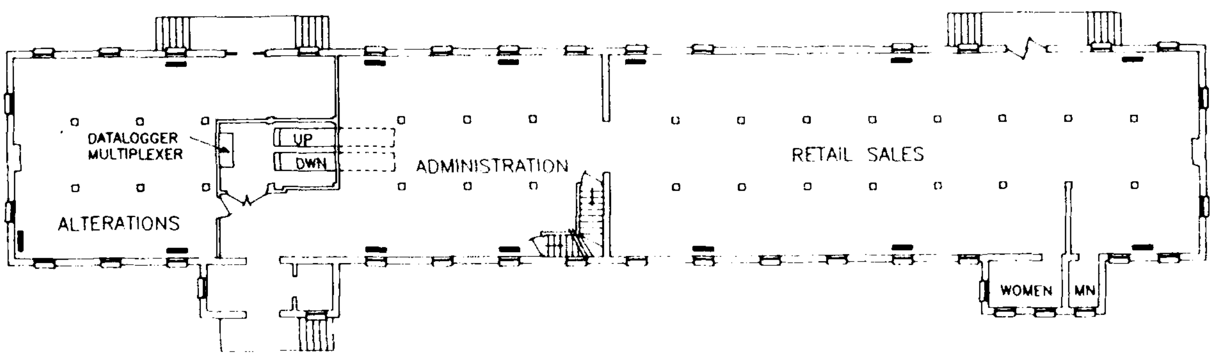


Figure 10. Building 17, first-floor plan.

Figure 11. Building 17, attic merchandise conveyor, looking down.

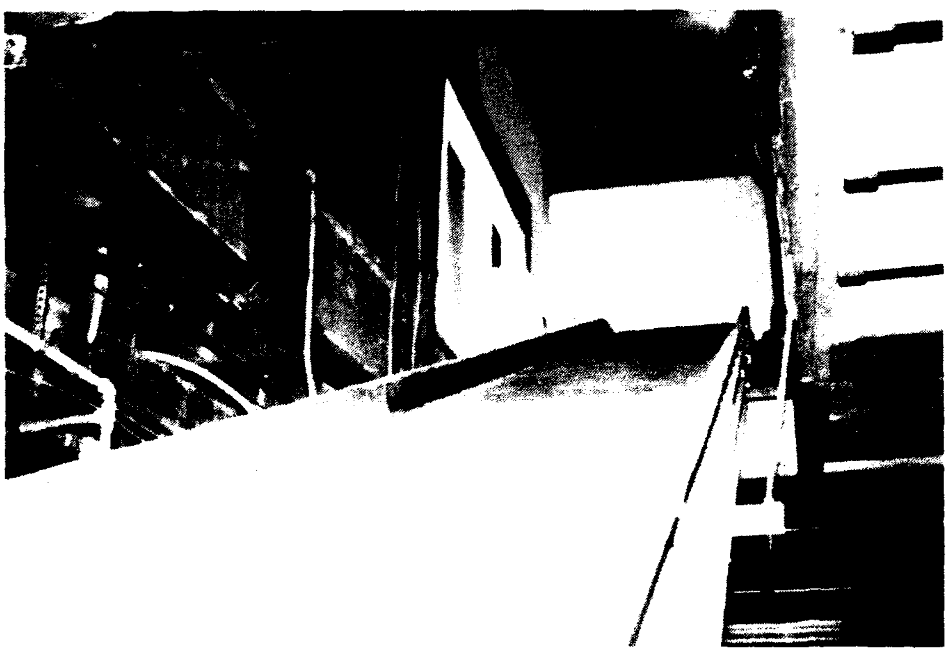


Figure 12. Building 17, basement merchandise conveyor, looking up.

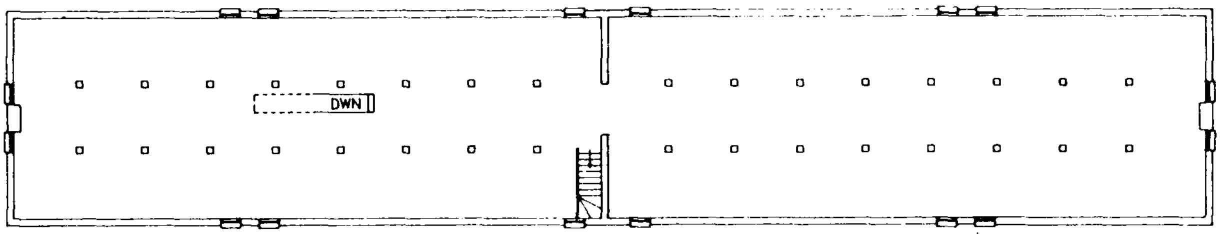


Figure 13. Building 17, second-floor (attic) plan.

Figure 14. Building 17, attic merchandise storage, looking west.

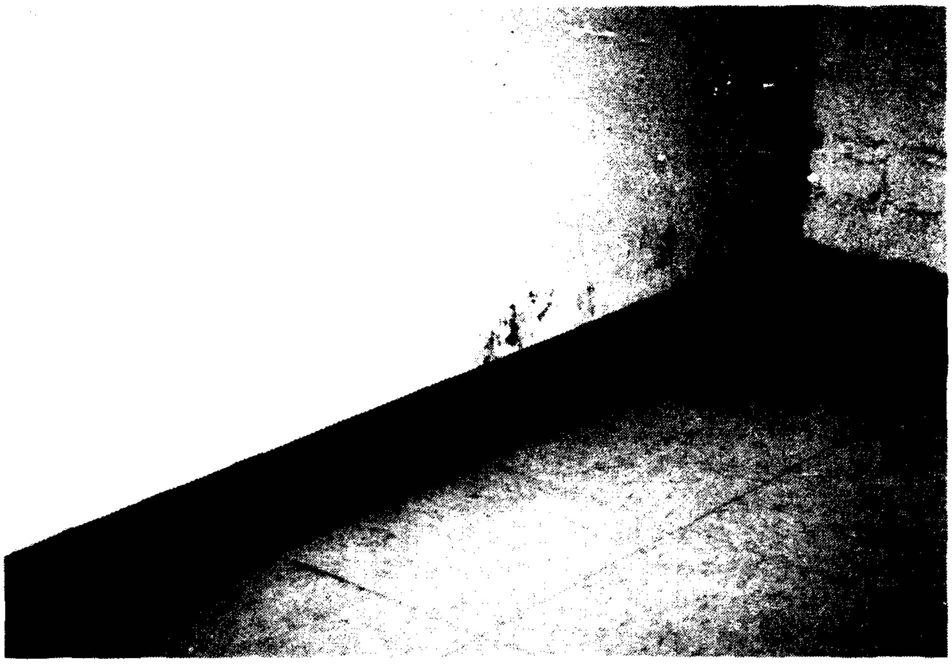


Figure 15. Moisture damage (mildew) in basement fitting area.

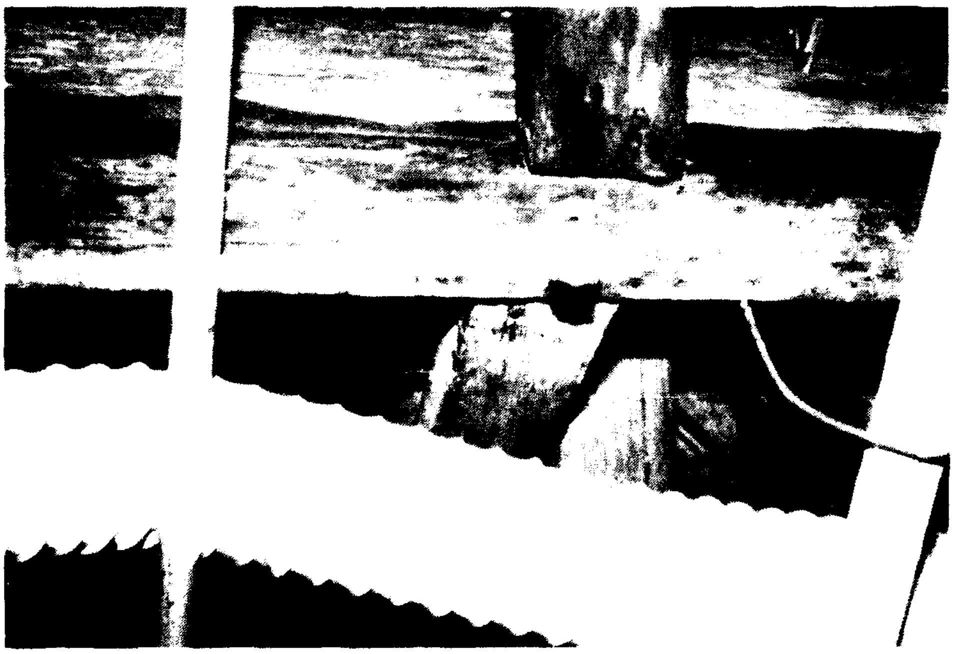


Figure 16. Moisture damage (wet/dry cycle) to floor joists, first floor.

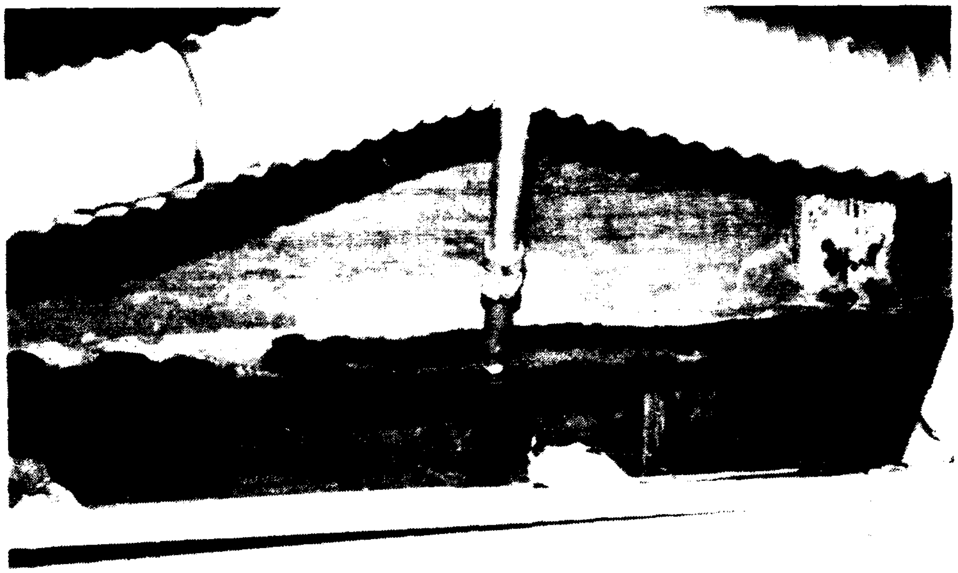


Figure 17. Moisture damage (wet/dry cycle) to floor joists, first floor.

Figure 18. Moisture damage (wet rot) in basement latrine.

4 DATA COLLECTION AND TRANSFER

Equipment Requirements

The first equipment requirement for this study is a digital data-collection device to collect and store large quantities of data, over an extended period, from an array of sensors placed in remote locations in a building. For processing and evaluation the data collected must be in a format appropriate for downloading to an IBM DOS*-compatible microcomputer. The second equipment requirement is that sensors chosen must be capable of delivering readable, unaltered signals directly to the collection device. The third requirement is that the equipment chosen must be capable of using battery power in case the test site has no power source readily available or power outages occur.

Equipment Selection Process

To avoid duplicating efforts, researchers in other divisions at USACERL who were working on studies involving data-collection techniques were contacted for their comments on the equipment requirements. From these conversations the researchers compiled a list of manufacturers known to produce equipment that might be applicable. These manufacturers were contacted and documentation was collected. The equipment under consideration was evaluated using the equipment requirements previously identified. When possible, current users of the equipment were contacted for their comments on the potential choices. Based on all of this information, the researchers procured the hardware described in the following paragraphs.

Datalogger and Multiplexer

A Campbell Scientific 21X Micrologger is being used for sensor control, data collection, and data storage on site. It is a programmable datalogger capable of accurately converting analog sensor signals to appropriate digital values, processing the measured values over a given period, and storing the values in memory. The 21X has 48K of memory for program and data storage, and it can be downloaded or reprogrammed via telephone using a modem. The 21X has a wide application range making it ideal for this application. In a normal configuration the 21X is capable of controlling eight sensors.

An AM-32 Multiplexer from Campbell Scientific is being used for sensor switching and control. Up to 32 sensor inputs can be multiplexed into the 21X using this piece of equipment. The AM-32 is capable of handling a wide range of sensor types. As each sensor is activated, the value is processed, and the result is placed in memory. By using two AM-32s, a single 21X is capable of sensing 64 separate locations.

*Disk Operating System.

Wetness Sensor

The Leaf Wetness Sensor Model 237 from Campbell Scientific was chosen to determine surface wetness. It is a three-wire resistance sensor. This type of sensor reads the voltage dropped across the wetness sensor surface—a variable resistor comprising a circuit board of interlacing fingers of gold-plated copper—and stores that value in a datalogger. As a surface goes from dry to wet, the resistance changes from a high of 3,000,000 ohms to a low of less than 1000 ohms. As surface wetness increases, the voltage read across the resistor changes inversely from low to high, based on the original source voltage.

Temperature/Humidity Sensor

Sensing for temperature and relative humidity will be accomplished with a Model HX91 two-wire transmitter from Omega Engineering. It can read temperature and humidity simultaneously. A calibration unit, Model HX91-CAL, will be used bimonthly to maintain sensor accuracy. The schedule will be adjusted if more frequent recalibration is found necessary. The data collected during any period when sensor accuracy is suspect will be analyzed separately.

Equipment Configuration

The 21X datalogger uses a six-wire connection to the AM-32 multiplexer and a 1000 ohm 5 percent resistor. Figure 19 illustrates the connections. This configuration is used to take an AC half-bridge voltage reading from the wetness sensor. Channels 1–28 of the multiplex, will be dedicated to the wetness sensors, with the remaining four channels reserved for the HX-91 temperature/humidity sensors. These sensors will be read in the same way as the wetness sensors, but their data will be processed by a different instruction set.

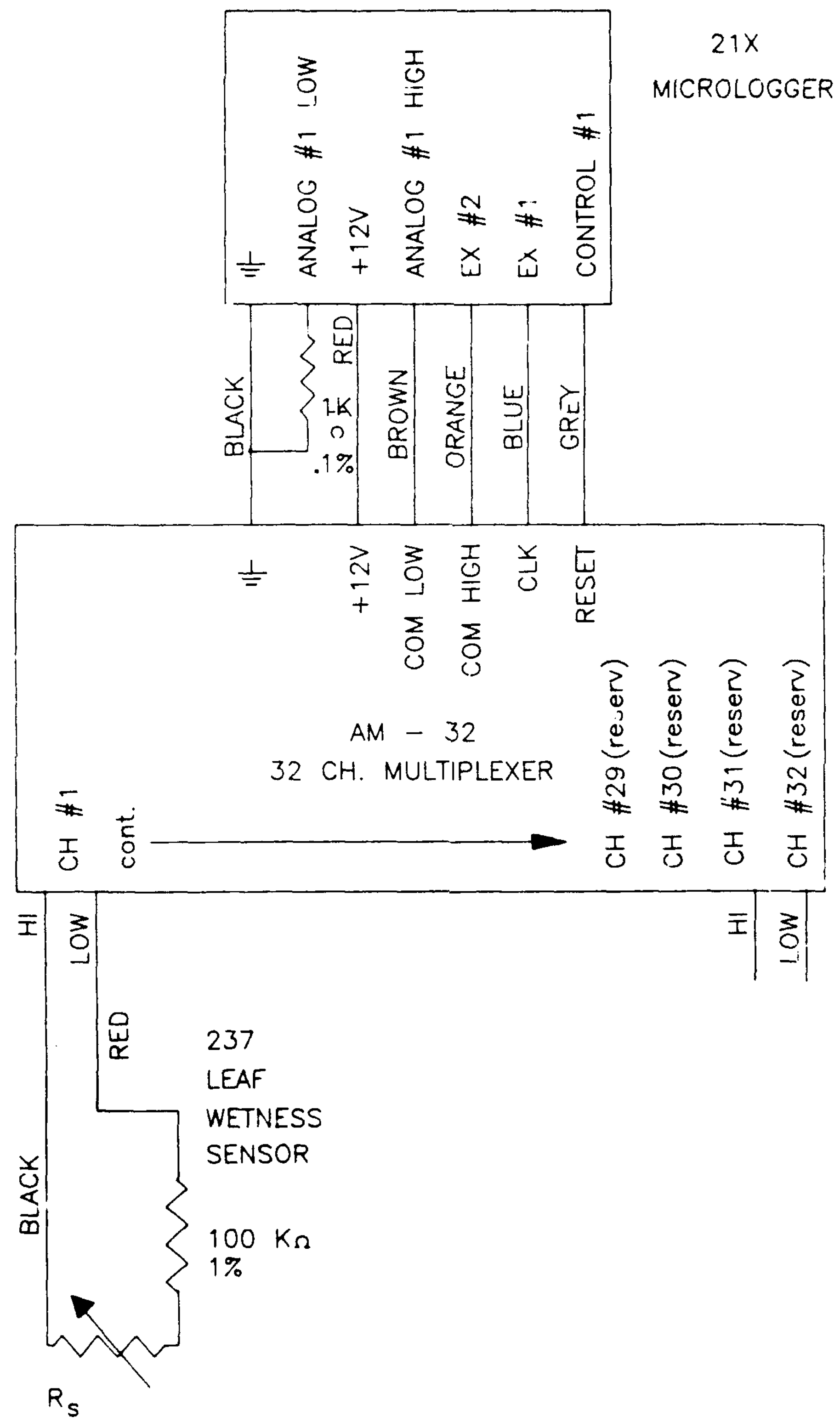


Figure 19. Equipment schematic and wiring diagram.

5 DATA EVALUATION

Data Values

The analog values returned by the sensors to the datalogger are initially processed to yield digital values between zero (completely dry) and one hundred (completely wet). At 20-second intervals each sensor is read in turn, and the value read is stored in temporary memory in the datalogger. After 15 repetitions, or 5 minutes, the values for each individual sensor are averaged. The averaged values are placed in a dedicated segment of memory for later downloading. This processing routine is used because most cases of moisture damage occur over an extended period. Therefore, the event need not be tracked at greater frequency. However, the collection and processing time schedule can always be revised if more or less frequent sampling appears necessary. All values are stored in ASCII format.

Initial Analysis

A spreadsheet program such as *Lotus 1-2-3* will check each downloaded data file for errors. Files with values outside the 0—100 range by more than 1 will be flagged for more rigorous error checking. If two consecutive raw data files are found to have errors, the hardware will be checked under the assumption that some unwanted variation in sensor performance may be occurring. If the hardware is found faulty, the offset and multiplier in the processing instructions will be adjusted to correct for the error. Individual pieces of hardware will be replaced in cases of rapid deterioration or failure.

Error-checked data files will be processed with *MathCad* to plot and analyze trends using 30-day cycles. These 30-day evaluations will be re-evaluated quarterly for longer-term trends that may not be evident in the shorter time frame. At the end of the third quarter of data collection and analysis, preliminary predictive evaluations will be initiated to start the feasibility evaluation of the overall system.

6 SUMMARY

This interim report describes the testing methodology, site selection, equipment selection, procedures for data collection and transfer, and approach to data evaluation for the testing of a sensing system for remote detection and analysis of moisture-related damage to a test structure at Fort Benjamin Harrison, IN. The conclusions and recommendations resulting from the findings and analysis of the data to be collected will be part of the technical report published after the completed test.

The final technical report will be prepared and published at the conclusion of the data collection period. The report will analyze data collected for cyclical changes and variations, extremes, medians, trends, and other patterns that may relate to the overall physical condition of the building. The final documentation of the study will include an evaluation and analysis of current technology available to sense building conditions of interest, collect and store data, and transmit that data to a remote location for further processing. Specifically, the final report will:

1. Evaluate current technology available to sense building conditions and collect and transmit data

2. Determine what types of data can be collected, and the best mechanism through which they can be collected

3. Determine what information can be derived from data collected

4. Determine threshold values to identify deteriorating building conditions that may require corrective action

5. Design algorithms to schedule maintenance and repair and inspections

6. Make recommendations for potential use, based both on the cost-effectiveness of the system for new construction and as a retrofit application to existing structures

7. Identify applications of this technology to other areas of the Army, such as quality assurance evaluators of commercial activities in DEH operations.

METRIC CONVERSION TABLE

1 in. = 25.4 mm
1 ft = 0.305 m
°F = (°C + 17.78) x 1.8

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